The University of Sydney

ELEC5206 Sustainable Energy Systems
Group Assignment

Lecturer:
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Techno-economic feasibility analysis of a small-scale PV-battery system

Assignment Description

Given the increasing electricity prices [1] and dropping costs of solar PV and battery storage [2, 3, 4], self-generation is becoming an increasingly sound proposition [5, 6, 7]. In Australia, this is further driven by the reduction of residential PV feed-in tariffs. AEMO predicts that three out of four new solar households will add battery storage in the near future [8, 9].

Your task will be to design a PV-battery system for a given residential/commercial building. Each group will need to consider one of the cases below (*groups will be determined after Week 3*):

- Residential building:
  - Young family (2 pre-school children, stay-at-home-mum, working father),
  - Wealthy family (2 teenagers, both mum and dad working, swimming pool),
  - Young couple (no kids, both working),
  - Retired couple;
- Small commercial building:
  - Butcher shop with a large refrigeration facility,
  - Grocery store,
  - Car service workshop;
- Large commercial building:
  - Shopping mall;
- Government:
  - School,
  - University,
  - Hospital.

The study consists of the following tasks, described in more detail later in the document:

1. Determine the location of the building;
2. Determine the available solar resource at the chosen location;
3. Estimate the electric power requirements of the building;
4. Analyse the electricity price and feed-in-tariff;
5. Design the PV/battery system;
6. Design the energy management system (EMS);
7. Determine the economic viability of the project by means of a cash-flow analysis.

Note:

- Even though this is a learning exercise, you should use real data as much as possible. In some cases you will have to "guestimate" but this should be your last resort. The estimates should be substantiated by references and sound engineering reasoning.
- This is a ***group assignment***, and team work will be an important assessment component.
- You should preferably find an existing building in your area that best matches your case. When approaching the owners, be polite and patient. **Under no circumstances should you inspect (let alone enter!) the building without an explicit permission of the owner.** You may want to show the owner this document and give them my contact details (`gregor.verbic@sydney.edu.au`, mobile: 0449 232 147).

1 Assignment tasks

1.1 Determine the location of the building

You may use Google maps to estimate the available rooftop area and the orientation of the roof, as shown in Fig. 1. Specific points to be considered in the design:

- orientation and inclination of the roof,
- possible shading,
- available rooftop area.

Figure 1: The available rooftop area can be easily determined using Google Maps.

1.2 Determine the available solar resource at the chosen location

To properly size a PV system, you will first need to determine the available solar resource [10], i.e. how much energy (and power!) can the system possibly generate at the chosen location [11]. Given the exact geographical location of the building and the orientation of the roof where the PV system is going to be mounted, you will need to calculate the available power production of the PV system at any given point in time (with at least half-hourly resolution).

You will need to take into account the following:

1. the position of the sun at any given point in time,
2. possible shading of the surrounding trees and buildings,
3. temperature effects (that will affect de-rating of the PV module and heating/cooling requirements of the building),
4. cloud coverage [12] (You can use daily peak sun hours as a proxy. Go to BOMs Climate Data Online [13] and look for daily global solar exposure for the site closest to your building).

These topics are covered in [14] and will be discussed extensively in the course.

To capture the seasonal, intra-weekly and intra-daily variations, it is important to model the PV generation and the demand as a time series with at least half-hourly resolution. One possible approach is to generate solar isolation time series for a typical year, using weather data from the Bureau of Meteorology [13]. To facilitate the analysis, weather data for several locations in NSW will also be provided. The data include temperature, wind speed and direction and cloud coverage with half-hourly resolution for the period of January 2012 to July 2014. For validation, compare the results for the given location with: (i) a simplified peak-hour approach, and (ii) with the weather data in EnergyPlus format with an hourly resolution for "typical meteorological months" (30 year average) [15]. The results might look something like the top graph in Fig. 2. Note that in this particular case, the time-series slightly overestimated the available solar insolation.

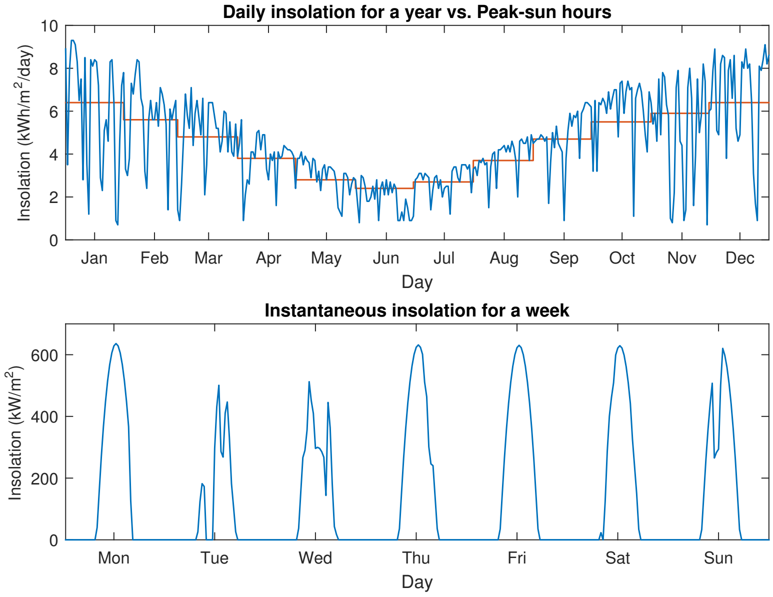

Figure 2: Solar insolation time series vs. peak hours (top), weekly solar insolation (bottom).

The bottom graph in Fig. 2 shows the instantaneous solar insolation for a week. You can see how cloud coverage affects the insolation.

1.3 Estimate the electric power requirements of the building

To determine the size of the PV-battery system given the available solar resource, you will need to estimate both the electric energy and electric power requirements of the building. If possible, find a representative building in your area and talk to the owners to get a good understanding of the consumption patterns. Think of the devices that use a lot of power, e.g. a pool in a residential building, a refrigeration facility in a local butcher shop, etc.

A good way to estimate the power consumption is to look at the power bill. The bill, however, will only give you the bulk power consumption, so you will have to find a way of disaggregating that into a time-series. A possible approach is to use typical seasonal demand curves, shown in Fig. 3. Also, keep in mind that working-day demand profiles typically differ form weekend profiles.

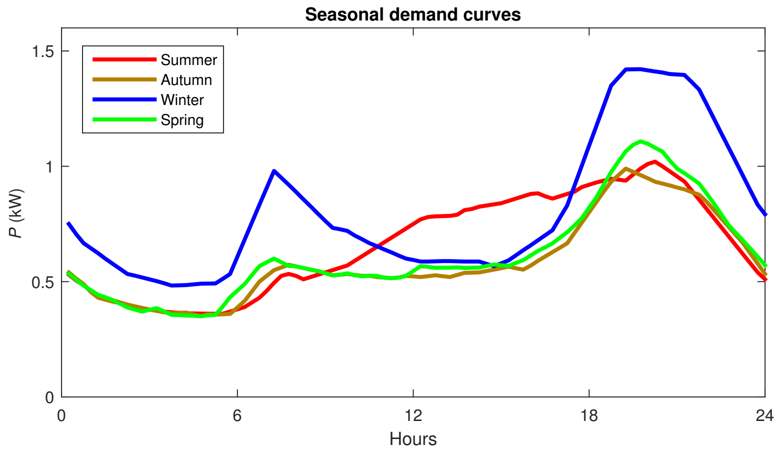

Figure 3: Seasonal demand profiles.

1.4 Analyse the electricity price and feed-in-tariff

Two of the factors that have the biggest impact on the profitability of a PV-battery system are the price of electricity and the feed-in-tariff, respectively. Do some research on the tariff structures offered

by the utilities [16] and the available feed-in-tariffs [17]. Note that these have been reduced significantly in the recent past and can be dramatically lower than even a couple of years ago! Starting with the existing tariff structure (the one the building is using at the moment), propose a tariff structure that would better suit the given demand profile.

1.5 Design the PV/battery system

Considering the above, you need to design the following main components:

1. PV panels,
2. inverter,
3. battery system.

Contact a local company or use the web [18, 19, 20, 21] to find the prices and the parameters. Use real data as much as possible!

Specific points to be considered in the design:

1. Show the connection diagram of the PV/battery system. The arrangement of the modules into strings and the converters needs to be clearly shown;
2. Battery system (the optimal size will be determined using the energy management system);
3. Check the equipment rating for extreme situations (e.g. temperature effect on the min/max voltage of the PV panel and whether it violates the inverter's limits, etc.);
4. Charging constraints of the battery system (fast charging/discharging can significantly shorten battery's life-cycle).

1.6 Design the energy management system

After you have designed the PV system, assume a battery management system (EMS) to better utilise the energy generated by the PV system. The role of the EMS is to determine the optimal charging profile of the battery system so that self-consumption of the PV power is maximised at times when energy prices are high. A fully functional Matlab implementation of the EMS will be provided. The optimisation horizon considered is one day.

The EMS is cast as an optimisation problem whose objective is to minimise the energy expenditure over the decision horizon (1):

$$\sum_{i=1}^{n} (p_{\mathrm{g},i}^{+} c_{\mathrm{g},i} - p_{\mathrm{g},i}^{-} c_{\mathrm{pv}}), \tag{1}$$

where n is the number of time steps (48 for one day with half-hourly resolution), $p_{\mathrm{g},i}^{+}$ is power taken from the grid, $p_{\mathrm{g},i}^{-}$ is power returned to the grid, $c_{\mathrm{g},i}$ is the retail tariff, and c_{pv} is the feed-in-tariff (FiT), all at time step i.

Decision variables are both continuous (2) and binary (3):

$$p_{\mathrm{g}}^{+}, p_{\mathrm{g}}^{-}, p_{\mathrm{b}}^{+}, p_{\mathrm{b}}^{-}, p_{\mathrm{b}}^{\mathrm{d}}, p_{\mathrm{b}}^{\mathrm{g}}, d_{\mathrm{pv}}, e_{\mathrm{b}} \in \mathbb{R}_{+}^{n}, \tag{2}$$

$$d_{\mathrm{g}}, s_{\mathrm{b}} \in \{0,1\}^{n}. \tag{3}$$

The optimisation problem is subject to the following constraints:

- equality constraints:

$$p_{\mathrm{g},i}^{+} = p_{\mathrm{d},i} - \eta_{\mathrm{i}} \left(\eta_{\mathrm{b}} p_{\mathrm{b},i}^{\mathrm{d}} + d_{\mathrm{pv},i} p_{\mathrm{pv},i} - p_{\mathrm{b}}^{+} \right) \tag{4}$$

$$p_{\mathrm{g},i}^{-} = \eta_{\mathrm{i}} \left(\eta_{\mathrm{b}} p_{\mathrm{b},i}^{\mathrm{g}} + \left(1 - d_{\mathrm{pv},i}\right) p_{\mathrm{pv},i} \right) \tag{5}$$

$$p_{\mathrm{b},i}^{-} = p_{\mathrm{b},i}^{\mathrm{d}} + p_{\mathrm{b},i}^{\mathrm{g}} \tag{6}$$

$$e_{\mathrm{b}}^{i} = e_{\mathrm{b}}^{i-1} + \Delta t \left(p_{\mathrm{b},i-1}^{+} - p_{\mathrm{b},i-1}^{-} \right) \tag{7}$$

$$e_{\mathrm{b},1} = e_{\mathrm{b}}^{\mathrm{start}} \tag{8}$$

$$e_{\mathrm{b},n} = e_{\mathrm{b}}^{\mathrm{end}} \tag{9}$$

- inequality constraints:

$$p_{\mathrm{g},i}^{+} \leq \bar{p}_{\mathrm{g}} d_{\mathrm{g},i} \tag{10}$$

$$p_{\mathrm{g},i}^{-} \leq \bar{p}_{\mathrm{g}} \left(1 - d_{\mathrm{g},i}\right) \tag{11}$$

$$p_{\mathrm{b},i}^{+} \leq \bar{p}_{\mathrm{b}} s_{\mathrm{b},i} \tag{12}$$

$$p_{\mathrm{b},i}^{-} \leq \underline{p}_{\mathrm{b}} \left(1 - s_{\mathrm{b},i}\right) \tag{13}$$

- upper and lower limits on the continuous variables:

$$0 \leq p_{\mathrm{g},i}^{+} \leq \bar{p}_{\mathrm{g}} \tag{14}$$

$$0 \leq p_{\mathrm{g},i}^{-} \leq \bar{p}_{\mathrm{g}} \tag{15}$$

$$0 \leq p_{\mathrm{b},i}^{+} \leq \bar{p}_{\mathrm{b}}^{+} \tag{16}$$

$$0 \leq p_{\mathrm{b},i}^{-} \leq \bar{p}_{\mathrm{b}}^{-} \tag{17}$$

$$0 \leq p_{\mathrm{b},i}^{\mathrm{g}} \leq \bar{p}_{\mathrm{b}}^{-} \tag{18}$$

$$0 \leq p_{\mathrm{b},i}^{\mathrm{d}} \leq \bar{p}_{\mathrm{b}}^{-} \tag{19}$$

$$0 \leq d_{\mathrm{pv},i} \leq 1 \tag{20}$$

$$\underline{e}_{\mathrm{b}} \leq e_{\mathrm{b}} \leq \bar{e}_{\mathrm{b}} \tag{21}$$

- integer variables:

$$d_{\mathrm{g}}, s_{\mathrm{b}} \in \{0, 1\}. \tag{22}$$

The decision vector $x = \left[p_{\mathrm{g}}^{+}, p_{\mathrm{g}}^{-}, p_{\mathrm{b}}^{+}, p_{\mathrm{b}}^{-}, p_{\mathrm{b}}^{\mathrm{g}}, p_{\mathrm{b}}^{\mathrm{d}}, d_{\mathrm{g}}, d_{\mathrm{pv}}, s_{\mathrm{b}}, e_{\mathrm{b}}\right]^{\top}$ consists of:

- $p_{\mathrm{g}}^{+/-}$: power flowing from/to grid,
- $p_{\mathrm{b}}^{+/-}$: battery charge/discharge power,
- $p_{\mathrm{b}}^{\mathrm{g}}$: power flowing from battery to grid,
- $p_{\mathrm{b}}^{\mathrm{d}}$: power flowing from battery to demand,
- $d_{\mathrm{g}} \in \{0, 1\}$: direction of grid power flow (0: demand→grid, 1: grid→demand),
- $d_{\mathrm{pv}} \in [0, 1]$: proportion of PV power flow (0: all PV power flows to grid, 1: all PV power flows to demand),
- $s_{\mathrm{b}} \in \{0, 1\}$: battery charging status (0: discharge, 1: charge),
- e_{b} battery state of charge.

Given that FiTs in Australia are significantly lower that the retail tariffs, the EMS effectively maximises self-consumption of the power generated by the PV system, which is shown in Figs. 4 and 5.

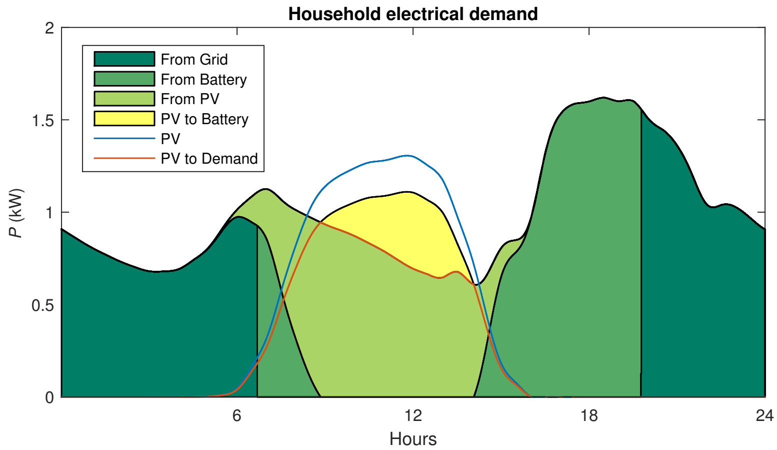

Figure 4: Household electrical demand by sources.

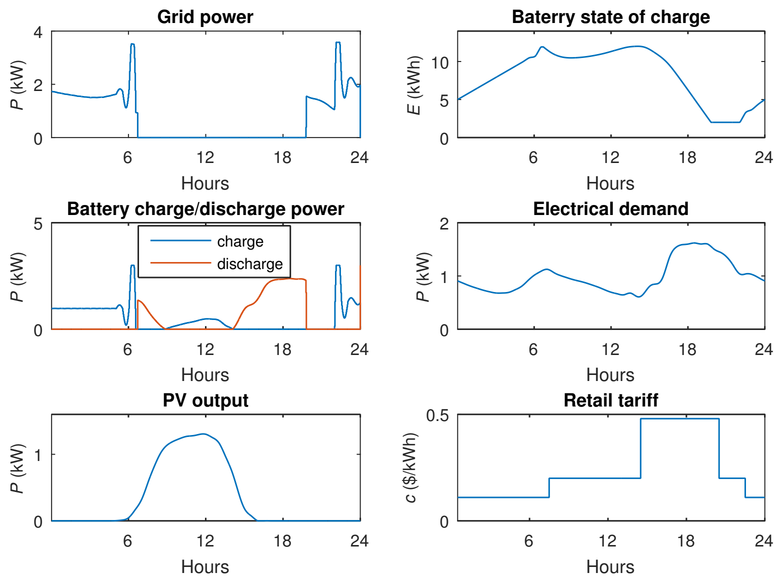

Figure 5: Some key variables of the EMS.

As you can see, the EMS tries to use as much PV power as possible. When this exceeds the demand (shown in yellow in Fig. 4), it charges the battery. That energy is then used latter in the evening when the retail tariff is the highest (the lower right plot in Fig 5) to minimise energy expenditure.

A schematic diagram and the power flows of the EMS are shown in Fig. 6. Also shown are the power flows between the various components of the system and the grid. Note that the battery and the PV system have each its own inverter. Alternatively, a system with a common inverter is also possible.

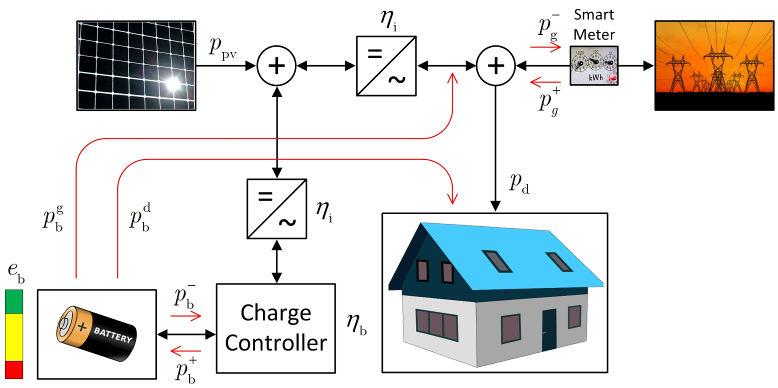

Figure 6: Schematic diagram and the power flows of the energy management system.

In order to solve the optimisation problem using an appropriate solver, it needs to be put in a standard form. More abstractly, the home energy management problem is a mixed-integer linear optimisation problem of the form:

$$\begin{aligned}
\underset{x_{\mathrm{r}},x_{\mathrm{b}}}{\text{minimise}} \quad & c^{\top}x \\
\text{subject to} \quad & \underline{x}_{\mathrm{r}} \le x_{\mathrm{r}} \le \bar{x}_{\mathrm{r}} \\
& Ax \le b \\
& x_{\mathrm{b}} \in \{0,1\}^{n_{\mathrm{b}}} \\
& x_{\mathrm{r}} \in \mathbb{R}_{+}^{n_{\mathrm{r}}}
\end{aligned}$$

where x_{b} and x_{r} are binary and continuous decision variables of the problem, respectively.

This form is very close to the form required by optimisation modelling languages. In this project, you will build the optimisation model in Matlab, and solve it using either Matlab [22] or Mosek [23] (both sample codes are provided).

In Matlab, the optimisation problem should be in the following form:

```
x = intlinprog(f,intcon,A,b,Aeq,beq,lb,ub)

% min (over the decision vector x) f'*x subject to:
%  x(intcon)      are integer variables
%  A*x    <= b    are inequality constraints
%  Aeq*x   = beq  are equality constraints
%  lb <= x <= ub are bounds on the decision variables
%
% where:
%  f, x, intcon, b, beq, lb, and ub are vectors, and A and Aeq are matrices
```

To help you get up to speed with using Matlab's Optimisation toolbox, I would suggest two MathWorks (Matlab) webinars [24, 25].

1.7 Determine the economic viability of the project by means of a cash-flow analysis

The last bit is the cash-flow analysis to assess the economic viability of the project [14, 26]. In order to do this, you will need to determine the cash flows for the whole duration of the project (typically 20 years). A sensible approach is to calculate the cash flows for a typical year using the results from the EMS, and assume that all the years are the same weather-wise. Note that the electricity price

might change (increase) during the life-time of the project.

The results of the cash-flow analysis might look something like Fig. 7, where the upper graph shows cumulative cash flow and the lower one net cash flow.

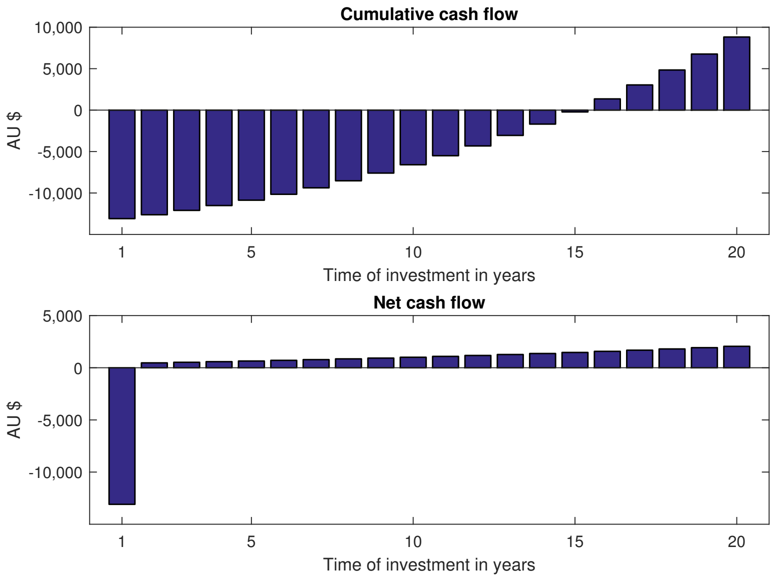

Figure 7: Cash-flows of the project.

1.8 Verification of the results using the AusGrid Solar Home dataset

In the Smart Grid Smart City project [27], Ausgrid collected PV generation and load data for 300 residential customers in an Australian distribution network, with load centres covering metropolitan Sydney and surrounding regional areas [28]. The dataset spans three meteorologically different years (2013 was sunnier that 2011 and 2012), with separately reported measurements of load and PV generation at 30-min intervals. The description of the data set is available in [29].

In your analysis, you assumed a "typical" meteorological year. To assess the impact of year to year weather variability, perform the economic viability assessment using PV measurements from the Ausgrid's data set. To make PV generation comparable, you will need to scale the data appropriately.

2 Team work and peer assessment

Group formation and team management will roughly follow the logic and principles discussed in [30]. In short, groups will be formed by the lecturer and no self-selection will be allowed. Engineering is a discipline where team work is essential, so you better learn it soon. Being able to work effectively with people you might have not met before is an important skill so take this as a challenge and a learning exercise. To cite [30]:

When you join a company, you will not be asked whether you prefer to work alone or with others, and you will not be presented with a list of all the employees and asked who you would like to work with. What will happen is that you will be assigned to groups of coworkers by your supervisor, and your job performance rating may depend more on how well you are able to work with those people than on any other ability you may have. Since that is what you will be doing in your careers, you may as well start learning how to do it now.

To avoid slacking off, every team member will get to evaluate their colleagues anonymously on a scale from 1–10. The weight will be summed up, normalised and multiplied with the group mark. For

example, in a group of five, if a particular student ends up doing very little and gets as a result the peer evaluation marks of 2, 3, 1, and 2, respectively, their final mark will be the group mark multiplied by 0.2. Large statistical variations (e.g. 10, 1, 9, 2 in the above example) will be dealt with individually. In other words, the lecturer reserves the right to disregard any ratings that look suspicious after attempting to understand the dynamics that produced them [30].

Peer assessment will be based on "team citizenship" of each member not on the relative contributions of the team members to the final product [30]. What that means is that you will be assessed on how well you cooperated with the team, how you fulfilled your responsibilities, helped others, etc. To cite [30] again:

If the weaker students on a team know that no matter how hard they try, their assignment grade will be lowered by the presence of stronger students on the team, many will be discouraged and/or resentful (rightly so) of the system putting them in that position. The "team citizenship" approach stresses teamwork skills over academic ability. If all team members act responsibly and cooperatively, they will all receive the team assignment grade; the only ones penalized by the system will be the hitchhikers and the other problem team members discussed earlier in this paper.

Peer-assessments should be submitted by email. Each group member should submit the assessment individually.

3 Deliverables

The deliverables include:

1. written report,
2. oral team presentation in front of the whole class,
3. Matlab code (one zip file) and MS Excel spread sheets (if used).

The maximum length of the report is 7,000 words, excluding the references. The appendices, figures and tables in the text don't count towards the word limit. Margins should be set to "MS Word normal", i.e. 2.54 cm all around. Font size should be 12, single spacing. For citations use EndNote (or similar) and IEEE style. In the report, you have to provide a written statement on the roles of the group members (who did what).

The presentation will be limited to 10 minutes (*depending on the class size, TBA*). Dont get bogged down in details. Make sure that you get the message across.

A fully functional Matlab code needs to be submitted to confirm the validity of the results. The code should include a single master m-file with subordinate files if needed. Calling the master m-file from Matlab command line should execute the code, export the results into mat-files and generate all the plots used in the report. Enough comments should be provided in the m-files to enable the use without much guessing. The cash-flow analysis can be done in MS Excel.

4 Assessment criteria

The assessment components are:

1. quality of the project and the report (60%),
2. oral presentation (20%),
3. Matlab code (20%),
4. team work (weighting according to the peer assessment).

The report should be written for a decision maker who is interested in investing in the project. The assessment will thus be based on whether the report provides all the relevant information to help the potential investor in making the decision, and whether it is organised in a clear and meaningful fashion. *Make sure that you clearly explain how you did the analysis and what assumptions you made. As a guideline, you should provide enough details to enable reproduction of your results.*

When preparing the presentation, imagine that you are trying to convince a management board to invest in the project (or not to invest if economically non-viable). In the limited amount of time you have to convince them that your proposal is worth pursuing (or not). The assessment will thus be based on whether you are able to clearly identify the main "selling points" of the project (or hurdles if the project is not feasible).

The assessment of the Matlab code will be based on the following criteria: (i) it should be invoked from Matlab's command prompt; (ii) it should generate all the plots used in the report, and export the results into mat-files; and (iii) provide sufficient comments for the user to understand it.

5 Plagiarism warning

Do you own work and study. Heavy penalty will be applied to students who committed plagiarism—either share the marks among number of similar copies found or even no marks on this assessment component. The assignment should include a signed academic honesty sheet.

6 Assignment submission instructions

The deadline is 4 October 2016 (Monday) 5pm at the latest. Please submit the assignment through Blackboard. Go to the Research Assignment tab, click "View/Complete" and follow the instructions.

The name of the document should be `ELEC5206_2016_Assignment_Group{number}.pdf`, e.g. `ELEC5206_2016_Assignment_Group3.pdf`.

Along with a written project report, you need to submit Matlab files and data files, to allow me to reproduce your results. If the computation is split into several files (sub-routines), there need to be a "master file", e.g. `ELEC5206_2016_Matlab_Group3.m` executable from the command prompt. All the files should be placed in the same directory.

Failure to provide a fully functional Matlab code will result in a 20% mark deduction.

7 Further reading

The references below are not meant to be exhaustive but merely a starting point.

References

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